

INTERNAL SHOCKS IN THE JETS OF BLAZARS

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ABSTRACT. The development of instabilities leading to the formation of internal shocks is expected in the relativistic outflows of both gamma-ray bursts and blazars. The shocks heat the expanding ejecta, generate a tangled magnetic field and accelerate leptons to relativistic energies. While this scenario has been largely considered for the origin of the spectrum and the fast variability in gamma-ray bursts, here we consider it in the contest of relativistic jets of blazars. We calculate the expected spectra, light curves and time correlations between emission at different wavelengths. The dynamical evolution of the wind explains the minimum distance for dissipation ($\sim 10^{17}$ cm) to avoid γ - γ collisions and the low radiative efficiency required to transport most of the kinetic energy to the extended radio structures. The internal shock model allows to follow the evolution of changes, both dynamical and radiative, along the entire jet, from the inner part, where the jet becomes radiative and emits at high energies (γ -jet), to the parsec scale, where the emission is mostly in the radio band (radio-jet).

1. Hierarchical internal shock model

We propose that the *internal shock scenario*, which is the standard scenario proposed to explain the observed gamma-ray burst radiation (Rees & Mészáros 1994, Lazzati et al. 1999, Panaitescu et al. 1999), can work also for radio sources in general, and for blazar in particular. The central engine which gives origin to jets in radio sources may work intermittently, accelerating shells of plasma with slightly different mass, energy and velocity. Faster and later shells can then catch up slower earlier ones. In the resulting collisions a shock develops, converting some of the ordered bulk kinetic energy into magnetic field and random energy of the electrons which radiate.

The wind is treated as a sequence of $N = t_w/t_v$ shells, where t_w is the duration time of the wind ejection from the central source and $t_v \ll t_w$ is the average interval between consecutive ejections. Each shell is characterized by a mass M_j , a Lorentz factor Γ_j and an ejection time t_j . After setting the dynamics of the wind ejection, we calculate the radii where the shells collide, approximately given by:

$$R = \frac{2\alpha^2}{\alpha^2 - 1} \Gamma_{\min}^2 c t_v \quad \alpha = \Gamma_{\max}/\Gamma_{\min} \quad (1)$$

where $\Gamma_{\min} - \Gamma_{\max}$ is the range of bulk Lorentz factors of the shells. In the case of blazar jets $\Gamma \approx 10$ and $c t_v$ is assumed to be of the order of the dimension of the central engine $\approx 10^{14}$ cm (for a BH with $M \approx 10^9 M_\odot$). Thus the collisions start at $\sim 10^{16} - 10^{17}$ cm,

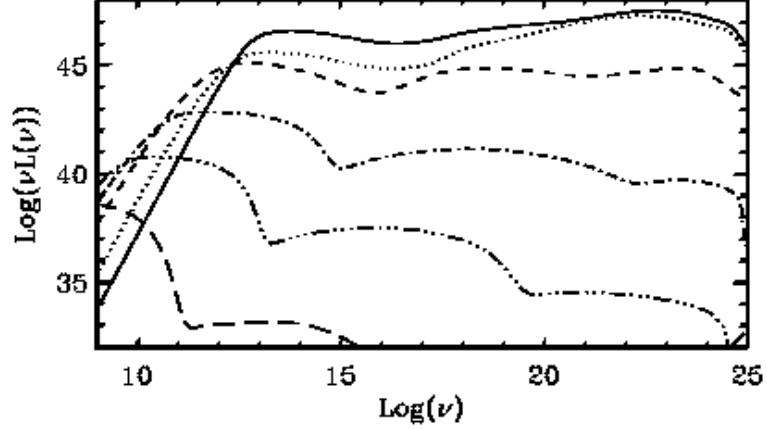


Fig. 1. Average spectrum produced in different regions of the jet: $R < 10^{17}$ cm (solid line), $10^{17} < R < 5 \times 10^{17}$ cm (dotted line), $5 \times 10^{17} < R < 2.5 \times 10^{18}$ cm (dashed line), $2.5 \times 10^{18} < R < 1.25 \times 10^{19}$ cm (dot-dashed line), $1.25 \times 10^{19} < R < 6.25 \times 10^{19}$ cm (3dots-dashed line), $R > 6.25 \times 10^{19}$ cm (long-dashed line).

in agreement with the estimates of the source size given by the observed variability and by the requirement of negligible $\gamma\text{--}\gamma$ collisions. The merged shells propagate on larger scales colliding again up to 10^{20} cm, where the differences among the shell velocities are completely smoothed out and the wind can be considered uniform.

For each collision we study the hydrodynamics, in order to determine the shock velocity, the compression ratio and the internal energy E_{sh} of the shocked fluid. Assuming a given partition of E_{sh} among protons, electrons ($E_e = \epsilon_e E_{sh}$, with $\epsilon_e \approx 0.5$) and magnetic field ($E_B = \epsilon_B E_{sh}$, $\epsilon_B \approx 0.04$), we calculate the relevant physical parameters in the shocked fluid and the emitted spectrum. The relativistic particles are assumed to have the same energy distribution (a broken power-law) throughout the entire emitting zone. This simplification does not allow to consider details of spectral changes on a timescale faster than the light crossing time of a single shell (few hours when $R \approx 10^{17}$ cm and a month on the parsec scale).

The relevant radiation processes are synchrotron, synchrotron self-Compton (SSC), and Compton scattering on the external radiation (EC), likely produced by the broad line region (BLR). The emission from each shocked region is assumed to last for the longest among the following timescales: the cooling time of the electrons, the time for the shock to cross the two colliding shells, and the time taken by photons to escape the source. We simulate the evolution of the total spectrum summing the locally produced spectra of those regions of the jet which are simultaneously active in the frame of the observer.

2. Results and Conclusions

In order to compare the results of the internal shock model with the observed spectrum and the temporal behavior of a powerful blazar such as 3C 279, we simulated a wind with an average kinetic luminosity $L_w \approx 10^{48}$ erg s $^{-1}$. The injection lasts for 10 years with an average interval between two consecutive shells of 3 hours (30000 shells in total). The shell Lorentz factors are random between $10 < \Gamma_j < 30$, the masses are also random with an average value of $M_j \approx 4 \times 10^{-3} M_\odot$, and we require a constant luminosity for the wind. This implies that more energetic shells are followed by longer quiet times, during which the central engine “re-charges”. The BLR has a radius of $R_{blr} = 5 \times 10^{17}$ cm and a luminosity of $\sim 10^{45}$ erg s $^{-1}$.

Since the Lorentz factors of the colliding shells are only slightly different ($\Gamma_{\max}/\Gamma_{\min} = 3$), the internal shock model is characterized by a low radiative efficiency: the fraction of kinetic energy converted into photons is less than 10%.

In Figure 1 we plot the average spectrum produced in different regions of the jet, in order to show the spectral evolution during the wind expansion. For the inner radii, $R \leq R_{blr}$, the external Compton emission dominates: most of the radiation is emitted at $10^{23} - 10^{24}$ Hz on time scales of the order of a few hours; the synchrotron spectrum peaks at $\sim 10^{14} - 10^{15}$ Hz, with a luminosity of $\approx 10^{46}$ erg s $^{-1}$. At larger radii only the synchrotron and the SSC (first and second order) processes contribute. The shell-shell collisions become less efficient as the distance increases, and the synchrotron peak shifts to lower energy, reaching ~ 10 GHz for collisions at 10^{19} cm. The time scale of the emission increases from few hours to few weeks, and the synchrotron dominates over the inverse Compton power at large distances.

The main observed properties explained by the internal shock model are:

1. **Low efficiency** — The radiative output of radio sources in general and blazars in particular must be a small fraction (say less than 10%) of the energy transported by the jet, since the extended radio structures require a power input much exceeding what is lost through radiation.
2. **Minimum distance for dissipation** — The bulk of the power we see must be produced at some distance ($> 10^{16}$ cm) from the jet apex and from the accretion disk. Otherwise the high energy γ -rays are absorbed by a dense radiation field leading to electron-positron pairs and to a softer (especially X-ray) radiation, which is not observed.
3. **Continuous energy deposition along the jet** — Dissipation occurs all along the jet: the γ -ray flux is produced mainly in the inner part, and can vary rapidly, while the radio flux is produced by the parsec scale jet, with a variability time scale of the order of weeks–months.

References

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